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# Optimisation of Opto-ULSI Processor Performance Using Closed-loop Feedback

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## Abstract

*In this paper, an algorithm based on multi-variable Newton-Raphson method is developed to optimise the steering efficiency of a 1-D Opto-ULSI processor. The algorithm enables the evaluation of the phase-voltage relationship of the Opto-ULSI processor using real-time power measurements. The optimisation algorithm reported in the paper is crucial for reconfigurable photonic systems such as optical add drop multiplexers, optical switches, tunable optical filters and WDM equalizers.*

## 1. Introduction

Optical beam steering is commonly accomplished via mechanical systems like mirrors on gimbals. As such systems tend to be large, heavy and complex, a non-mechanical all-electronic beam steering component would often be preferred [1]. One suggested technique to achieve this is by means of optical phased arrays (OPAs), where spatial phase modulation is applied onto an outgoing wavefront. A saw-tooth shaped phase pattern is readily designed to produce the same effect as a prism i.e., causing a deflection of an optical beam. By applying more complex phase patterns an optical beam can even be shaped or split into multiple beams [2].

The use of ultra-large-scale integration (ULSI) technology in conjunction with new mixtures of Liquid Crystals (LC) has recently led to the construction of polarisation-insensitive Opto-ULSI processors capable of steering, splitting and reshaping optical beams [3]. Opto-ULSI processors have several properties that are attractive for laser beam steering including a small pixel size, low-switching voltage, low power consumption, and high optical efficiency. For applications where high optical transmission is of importance nematic LC is commonly used in configurations permitting multi-level phase modulation. From an application point of view non-mechanical beam steering and beam shaping are desired features for many applications including free-space optical communications, laser pointing, 3D holographic memories, laser-based imaging and illumination system. Implementation on airborne platforms is of particular interest due to the requirements of low weight and volume and low power consumption.

This is of particular importance for lightweight airborne platforms such as e.g. unmanned aerial vehicles. The Opto-ULSI processor offers enhanced flexibility in future laser pointing and tracking systems. By combining beam shaping and tracking, new capabilities can be obtained. Another challenging feature may be obtained by splitting the beam into sub-beams in order to track several targets simultaneously. For a free-space optical communication system the Opto-ULSI processor can be used for beam steering and tracking. Ahderom et al. have demonstrated a 4-channel Opto-ULSI-based reconfigurable add/drop multiplexer [3].

In this paper, we explore the use of real-time closed-loop feedback to improve the performance of Opto-ULSI processors. An algorithm is developed to optimise the voltage profile of the Opto-ULSI processor for maximum diffraction efficiency. The algorithm is implemented using LabVIEW and includes a fully functional Newton-Raphson algorithm which lets a user enter a desired blazed grating pitch of up to 128 pixels.

## 2. Theory

A collimated beam propagating through a prism will be 'steered' in a direction opposite the tilt of the prism (Figure 1a). A prism can also be constructed with a thin film that has greater refraction index on one side than the other (Figure 1b). Opto-ULSI processors can electronically change the index of refraction profile of a thin electro-optical film thus realizing beam steering with no moving parts [4] (Figure 1c).

Liquid crystal is made up of long, skinny molecules. By changing the voltage across an LC cell, it is possible to rotate the orientation of these molecules and thus change the index of refraction for a given polarization. The major difficulty with LC is that switching speed of a nematic liquid crystal phase shifter is generally inversely proportional to the square of the thickness of the nematic liquid crystal layer. Therefore, for fast response, it is desired to keep the liquid crystal layer thin. This can be achieved by driving the LC with modulo- $2\pi$  sawtooth ramp [5], as shown in Figure 2. This modulo- $2\pi$  sawtooth ramp steers an optical beam with unity efficiency (no sidelobes), but only for the designed



wavelength for which the phase resets exactly equal  $2\pi$  radians.

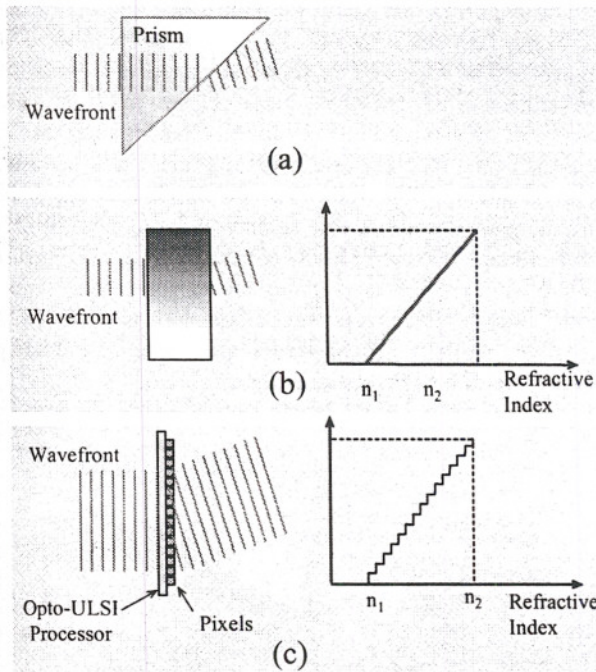


Figure 1 Beam steering through (a) a prism, (b) a graded index thin film, and (c) an opto-ULSI processor.

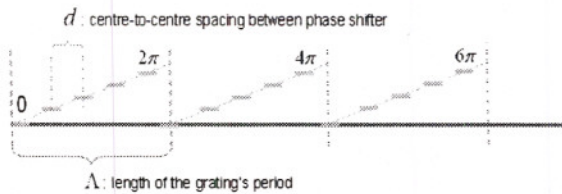


Figure 2. Pixilation of the phase ramp causes loss in beam steering efficiency

Quantisation into staircase-like blazed grating leads the generation of higher diffraction orders and hence a reduction in diffraction efficiency. The first order diffraction efficiency,  $\eta_{step}$  is given by [4]

$$\eta_{step} = \left[ \frac{\sin(\pi/q)}{\pi/q} \right]^2 \quad (1)$$

where  $q$ : number of step in the blazed grating profile. For example, a five step would give a theoretical efficiency of approximately 94%. The 6% energy loss is coupled into the various sidelobes or higher-order diffraction orders [5]. Finer quantisation gives higher efficiency and correspondingly lower sidelobe levels.

Liquid crystals suffer from fringing fields and resistance to rapid change in orientation, which makes it difficult to electronically address a liquid crystal array at

sub-wavelength spacing. This difficulty does not manifest during the uniform phase-ramp portion of the addressing process [4]. Instead, the difficulty comes at the reset point where abruptly drop in phase is desired. During the phase ramp, fringing field effects smooth the phase profile. At the reset point, the fringing field creates a spatial region with opposite phase profile as shown in Figure 3. The flyback steers the portion of an incident optical beam to an opposite angular position thus reducing the diffraction efficiency. For small steering angles (ie. small ramp slope), the flyback region is small percentage of the phase ramp and has a small impact on the diffraction efficiency. However, as the steering angle gets larger, a significant portion of the wavefront is coupled into higher diffraction orders, resulting in a significant reduction in diffraction efficiency and higher crosstalk.

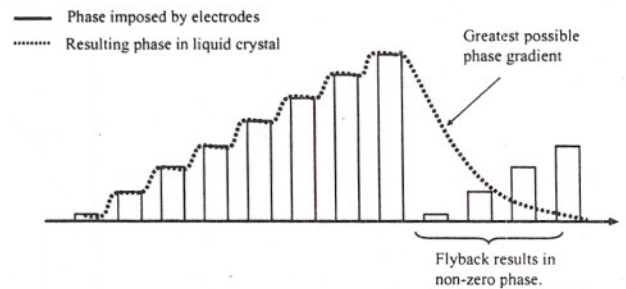


Figure 3. Phase profile due to fringing field and resistance of liquid crystal material to rapid change in orientation.

The overall diffraction efficiency due to quantization as well as the flyback effects can be approximated by [4]

$$\eta_{total} = \left[ \frac{\sin(\pi/q)}{\pi/q} \right]^2 \cdot \left( 1 - \frac{\Lambda_F}{q \cdot d} \right)^2 \quad (2)$$

Where

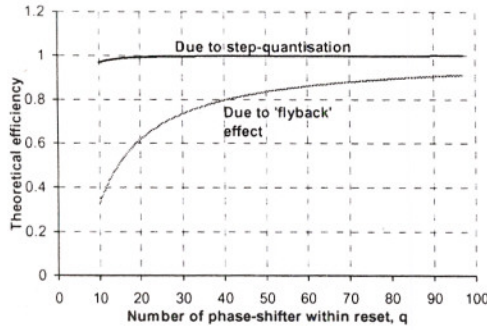
$\Lambda_F$ : width of the flyback region

$\Lambda$ : length of the grating period  $= q \cdot d$

Figure 4 shows the steering efficiency versus the number of pixels for an Opto-ULSI processor with and without the effects of flyback. It is obvious that the flyback significantly reduces the steering efficiency when the number of pixels is low.

Spacing at the half-wavelength level would allow large-angle beam steering without creating the detrimental flyback effect [2]. For optimal performance, the beam-steering capabilities of liquid crystal devices are currently limited to about  $5^\circ$  in either direction in order to maintain high efficiency beam steering.





**Figure 4. Steering efficiency versus number of pixels for a step-quantized Opto-ULSI processor with and without flyback.**

The application of a periodic sequence of staircase voltage ramps of period  $\Lambda$  across the array aperture (Fig. 2) which steers by an angle  $\theta$  (relative to the normal) given by the general grating equation

$$\sin \theta + \sin \theta_{inc} = \frac{\lambda_o}{\Lambda} \quad (3)$$

$$\text{or} \quad \theta = \sin^{-1} \left[ \frac{\lambda_o}{\Lambda} - \sin(\theta_{inc}) \right] \quad (4)$$

Where

$\lambda_o$  = wavelength in free space

$\theta_{inc}$  = angle of incidence

$\Lambda$  = grating's period =  $q \cdot d$

$q$  = Number of pixels within the grating's period

$d$  = centre-to-centre spacing between phase shifter

The steering angle  $\theta$  depends on the period length of the grating  $\Lambda$  (and sign) of the applied voltage ramp. The operation of the device is similar for receive and transmit mode.

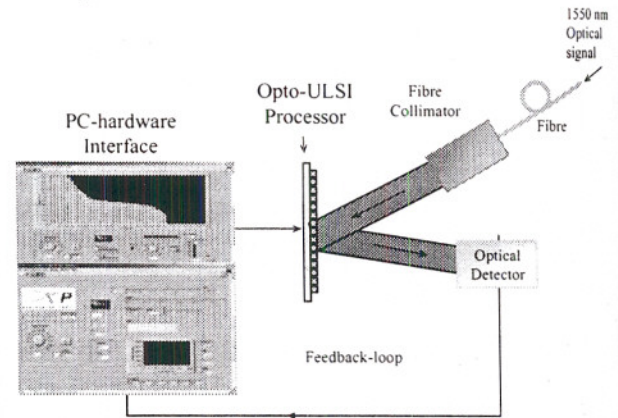
Efforts to improve the steering efficiency of Opto-ULSI processors can be broadly divided into two approaches. The first approach is based on ensuring that the phase ramp is truly linear, and the second approach takes into account the flyback effect at the  $2\pi$  resets to minimise the loss, thereby ensuring that the phase is properly reset to zero before it is being raised again.

The nonlinear response of the LC phase to an applied voltage can straightforwardly be measured using ellipsometry. However, this is a rather tedious task as it requires accurate measurements of many physical parameters which might not be readily available for commercial devices.

In this paper, we propose and assess a simple iterative method based on direct optical beam measurements in conjunction with closed-loop feedback to optimise the steering efficiency of Opto-ULSI processors.

### 3. Experimental setup

The experimental setup for optimising the diffraction efficiency of the Opto-ULSI processor is shown in Figure 5. The Opto-ULSI processor used is a reflective one-dimensional, 1x4096 pixel OPA from Boulder Nonlinear Systems (BNS Inc., USA). The device consists of 4,096 electrode strips that are 1  $\mu\text{m}$  wide and approximately 7 mm long. The electrode spacing is 1.8  $\mu\text{m}$  and each electrode can be driven by an 8-bit or 256-level voltage driver. Other apparatus were collimator with beam size 0.5 mm, polarisation controller, single-mode fibre, Newport power meter 1835C with GPIB interface, Agilent tunable laser source, and a desktop running MATLAB and LabVIEW.



**Figure 5. Experimental setup for diffraction efficiency optimisation.**

The wavelength is set to 1550 nm and is launched from the fibre collimator towards the Opto-ULSI processor at an incidence angle of approximately  $30^\circ$  with the normal. The photodetector was positioned in front of the Opto-ULSI processor to measure the optical power of either the zeroth order reflected beam when the power is switched off, or the  $-1^{\text{st}}$  order steered beam when the Opto-ULSI processor is driven by a blazed grating. The detected optical power is read by the computer via the GPIB (general purpose interface bus) and processed in MATLAB within LabVIEW environment. After measuring the detected power and the changes in detected power due to changes in individual pixel voltages, a new voltage profile is calculated using Newton-Raphson method and loaded into the Opto-ULSI processor, via its ISA board, for solution refinement.

### 4. Experimental work

#### 4.1 Optical intensity curve characterisation

The developed LabVIEW program allowed the voltage level of individual electrodes with the grating period to be controlled independently and the optical



intensity change as a function of the voltage level of a given electrode to be measured. The program also allowed the user to select the grating period and linear voltage ramp is used as the initial input. In our particular setup, a positive slope ramp voltage steered the incident light to the direction of the  $-1^{\text{st}}$  order while the negative slope ramp steered the light to the  $+1^{\text{st}}$  order diffraction angle. Since the multivariable Newton-Raphson method requires the derivatives of the optical intensity with respect to changes in voltage levels, optical intensity versus voltage profile curves were measured for blazed grating pitches (BGP) of 16, 24, 32 and 64. It was found that the change in optical intensity caused by a change in an electrode voltage can be broadly divided into three classes, namely, positive slope, negative slope and maximum turning point, as shown in Figure 6.

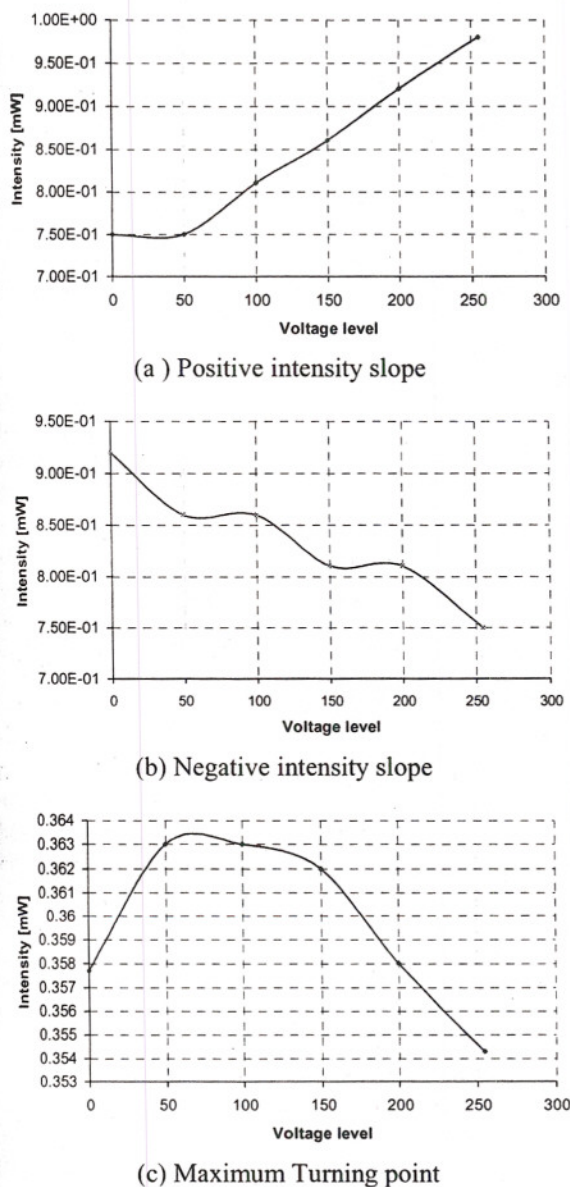


Figure 6. Typical optical intensity versus voltage level curves.

A gradient detection algorithm was developed and used to identify these categories and the optimised voltage values for category 1 and 2 were identified without having to perform lengthy calculation. To illustrate the concept of the gradient detection algorithm, suppose both the gradient around 0 and 255 voltage levels were found to be positive, then we can deduce that it is likely that the voltage profile belongs to category 1 where the intensity increases with input voltage. From the graph, we can see that for such voltage profile the maximum intensity happens at  $V = 255$ . Therefore, the algorithm will set  $V_{\text{optimised}} = 255$  if both gradients are found to be positive. Likewise, if both the gradient were found to be negative, we can deduce that the voltage profile belongs to category 2 where the maximum intensity occurs at  $V = 0$ .

The third kind of  $I$ - $V$  relationship involves one maximum turning point. In this case, the gradient around the vicinity of  $V = 0$  is positive but negative around  $V = 255$ . The voltage value at which the intensity is a maximum is found when the slope  $\frac{dI}{dV} = 0$ . A way to accomplish this is to work in the gradient plane, that is a plot of  $\frac{dI}{dV}$  vs.  $V$  and because the point of interest  $\frac{dI}{dV} = 0$  happens to be the root of the function, we can use Newton-Raphson method to find the value of  $V$  when  $\frac{dI}{dV} = 0$ . The use of Newton-Raphson method allows the solution to be found with a few iterations. The general iteration expression for Newton-Raphson method is

$$x_{n+1} = x_n - \frac{f(x)}{f'(x)} \quad (5)$$

Adapting equation (6) to our case, we have

$$V_{n+1} = V_n - \frac{\left(\frac{dI}{dV}\right)_n}{\left(\frac{d^2I}{dV^2}\right)_n} \quad (6)$$

## 4.2 Simulation test

To test the convergence of Newton-Raphson method operating in the gradient plane, we first setup an artificial system whereby the intensity is provided by a normal-distribution centred around the "optimum" value. Furthermore, the maximum difference in optical intensity was set to about 0.010 mW to simulate the actual environment (as in Figure 6c). It was found that if the starting point is within 50 levels from the optimum voltage  $V_{\text{opt}}$ , it practically converged to the optimum



point of  $V = 50$  in just one iteration. However, as the difference between  $V_{initial}$  and  $V_{opt}$  gets larger more iterations were needed to find the root, and eventually it diverges when the voltage difference is greater than 90 levels. The simulation results suggest that proper starting point is essential if convergence is to be met.

### 4.3 Noise Handling Issues

The use of Newton-Raphson iteration as a means to find the optimum voltage value of each electrode requires that the optical intensity to be reasonably stable for accurate measurements. The fluctuation in intensity reading is largely attributed to the laser source and the fact that the Opto-ULSI processor is constantly updating the voltage data from its memory. The noise level measurement was performed by averaging the intensity reading over a relatively-long time period. A typical measured intensity versus time is as shown in Figure 7. The approach used to minimise the reading error was to take five intensity measurements, and ensure that the standard deviation is less than  $10^{-4}$  mW. If the data set is found to be outside the specified standard deviation limit, a new set of intensity readings was acquired while all other parameters of the system being fixed. Figure 8 shows the effectiveness of the adopted standard deviation criterion on improving the accuracy of the algorithm. In this model, the intensity reading is supplied by a normal distribution centred around an 'optimum' value. We can see from Figure 8 that the standard deviation criterion results in an excellent agreement with theory by successfully determining the correct voltage level.

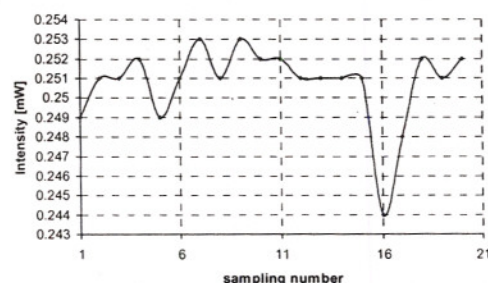


Figure 7. Typical fluctuations in optical intensity.

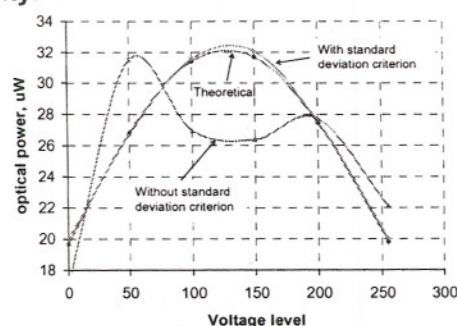
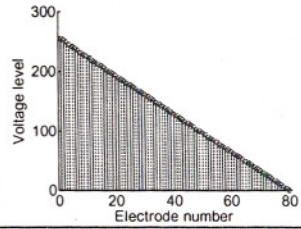
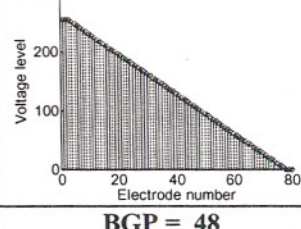
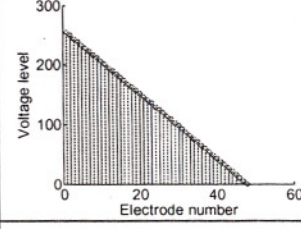
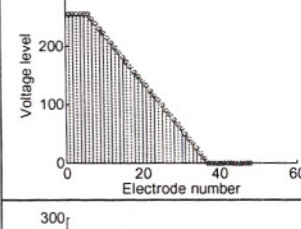
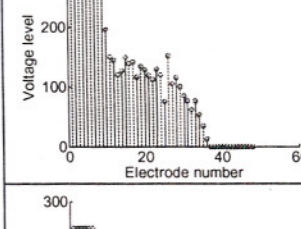
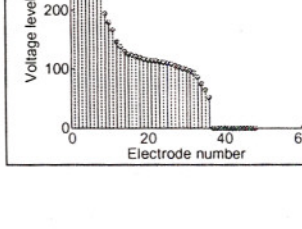


Figure 8. Theoretical and measured Optical intensity with and without the standard deviation criterion.

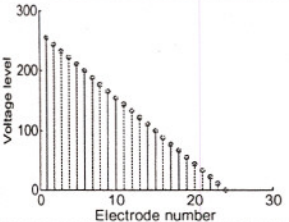
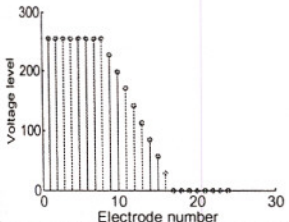
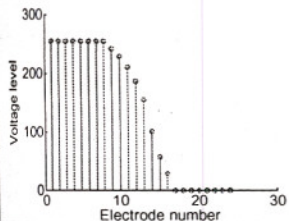
### 4.4 Global Optimisation Results

Table 1 shows the voltage profile and corresponding measured diffraction efficiency obtained from the multi-variable Newton-Raphson iteration method using real-time optical intensity measurements.

Table 1. Voltage profiles for various blazed grating pitches.

Voltage profile	Efficiency (+/- 0.5%)
<b>BGP = 80</b>	
	45.0%
	43.8%
<b>BGP = 48</b>	
	37.3%
	26.4%
	37.5%
	42.1%



BGP = 24	
	19.3%
	25.5%
	25.9%

It is clear from Table 1 that if both the flyback effect and the non-linearity in the phase-voltage relationship are properly taken into account, the steering efficiency does improve noticeably. For example, for BGP = 48, the linear voltage ramp produces an efficiency of 37.2%. However, if we attempt to optimise the ceiling and floor-plateaus, the efficiency drops to 26.4%. If we further optimise the phase ramp, the efficiency boosts up to 42%. A plausible explanation for this is that as the grating period gets longer, the phase ramp is the one that dominates the efficiency because the flyback region is largely a constant which is almost equals to the size of the thickness of the LC cell.

The factors that affect the steering efficiency of the Opto-ULSI processor are the flyback effect (due to fringing fields and viscosity of the liquid crystal), step-quantisation of the phase-ramp and the non-linear phase-voltage relationship. Depending on the grating period, these factors dominate the overall steering efficiency of the Opto-ULSI processor with varying degrees. As mentioned in reference [7], the diffraction efficiency of a Opto-ULSI processor is a combination of the fringing fields and elastic property of the LC material. The influence of elastic constant of the efficiency is very complicated.

As the BGP becomes smaller (larger steering angle) the nonlinear phase-voltage relationship produces less impact on the steering efficiency, and instead, it is the lengths of the plateaus that have the greater impact. This is evident from the comparison between the cases of BGP = 48 and BGP = 24 which are consistent with the fact that as BGP becomes smaller, the ratio of

$\frac{\Lambda_F}{\Lambda}$  increases which causes a high loss in the desired angular direction. Since the plateaus are directly related to  $\Lambda_F$ , their influence becomes significant as the grating period drops.

The Newton-Raphson algorithm as described in this paper does work both in simulated model whereby the intensity is supplied by a normal-distribution equation as well as in the real-system. The rather jagged profile we see in BGP = 48 can be further improved by setting a lower value of standard deviation limit.

By investigating the series of voltage profiles in the result Section, there seems to be a possibility of coming up with an even simpler algorithm. Since the general curvature of the ramp-voltage is known, albeit is possible to develop a polynomial based curve-fitting technique with adjustable constants and instead of optimising the individual electrode within the grating period, the algorithm can optimise the polynomial constants yielding a maximum intensity output in the desired angular direction. This curve-fitting technique may require high polynomial orders, which in turn requires relatively large number of electrodes, but this requirement is in line with the fact that it is only necessary to optimise voltage-ramp with high BGP e.g. 48, 64 or 128. This will be the core of future research.

Finally, the core of the optimisation program reported in the paper is intended to be used to control a multifunction MicroPhotonic system that realizes Reconfigurable Optical Add-Drop Multiplexing (ROADM) spectral equalisation and dynamic optical filtering.

## 5. Conclusions

We have developed and demonstrated a closed-loop feedback algorithm based on Newton-Raphson method to optimise the steering efficiency of an Opto-ULSI processor in real-time. Results have shown that the algorithm is effective in handling the optical intensity fluctuations and that the optimum voltage profile that maximizes the diffraction efficiency of an Opto-ULSI processor can now be automatically determined by simple real-time optical intensity measurements without the need of sophisticated measurements of the nonlinear characteristics of liquid crystal materials.

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